Fermilab FERMILAB-CONF-04-238-E NOVEMBER 2004

A Select Overview of Neutrino Experiments

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Abstract

The relationship between the lepton sector and the quark sector is an interesting source of discourse in the current theoretical climate. Models that might someday supersede the Standard Model typically require quark structure, with implications for the lepton sector. This talk will explore some of the consequences of newer models, in the context of certain neutrino experiments.

To set the stage for this discussion, please recall the words of Reginald Butler:

> There was a young lady named Bright,
> whose speed was far faster than light,
> She went out one day, in a relative way,
> and returned the previous night!

Talk given at the 13th International Seminar on High Energy Physics
"QUARKS' 2004"
Pushkinskie Gory, Russia, May 24-30, 2004

*This work was performed at the Fermi National Accelerator Laboratory, which is operated by the University Research Association, under contract DE-AC02-76CH03000 with the U.S. Department of Energy. Send comments to: stefanski@fnal.gov

1 Introduction

Why would we wish to discuss neutrinos at a seminar devoted to quarks?

In the Standard Model (SM) the quark and lepton sectors are clearly separated, each with its own unique properties. Both baryon number and lepton number are good quantum numbers. Leptons are treated as fundamental particles.

In an extension of the SM, such as Minimal SUSY, we may no longer conserve baryon or lepton number. Another conserved quantity such as R-parity may be used instead. It is defined as

$$P_R = (-1)^{3(B-L)+2S} \tag{1}$$

where S is the particle spin. All SM particles have P_R=1, while all super-particles have P_R=-1. Conservation of P_R implies that every interaction vertex has an even number of super-partners, and that a least massive particle (LMP) must exist [1]. If P_R is not conserved, then the LMP may be observable in neutrino decays [2].

Lepton experiments constrain SUSY parameters by measuring the neutrino mass in oscillation experiments, nuclear beta decay, or the neutrinoless double beta decay. The experiments also explore the spin properties of the neutrino vis-a-vis the Dirac/Majorana - particle/antiparticle characteristics. Precise measurement of muon decay, searches for neutrino decay, measurements of the anomalous magnetic moments, and the electric dipole moments of the leptons also constrain the models. Future experiments are likely to address the issues of CP and CPT conservation in the lepton sector by means of rare decays, neutron decay, and parity violating electron scattering. For example, if the neutrinos turn out to be Majorana particles with mass, theory must account for the possibility of neutrino decay, and the possible appearance of lepton violation.

2 Current Understanding

The successful detection of neutrino oscillations at SuperK [3], SNO [4], and KAMLAND [5] can be explained only if the neutrinos are massive. This discovery is an important step toward understanding the properties of neutrinos, but many questions remain unresolved. What is the number of neutrino flavors (three active and some sterile); is the neutrino a Majorana or Dirac particle; what is the magnitude of the masses, and what is the mass hierarchy; what are the neutrino flavor mixing parameters; what other exotic properties does the neutrino exhibit - does it decay, does it violate CP or CPT? At a recent seminar at Fermilab [6] Stephen Parke reported the result of his poll of theoretical opinion: Based on current prejudice there would be three neutrino flavors, the neutrino would be a Majorana particle, the see-saw [7] mechanism would properly explain the mass hierarchy, and there would be no exotic effects. His conclusion: "At least one prejudice must be wrong."

3 Neutrino Experiments

In this talk we wish to discuss the status and future of neutrino experiments, or at least a recent manifestation of some of them. We will not go so far into the past as to explore Fermilab E-531, CERN Chorus or NOMAD, although this history is very interesting in its own right [8]. Much of the early work regarding neutrino oscillations was done at BNL, CERN, Fermilab and Serpukhov. To begin, let's look at LSND [9] and Karmen [10].

3.1 LSND and KARMEN

The first observation of an appearance of an excess of $\bar{\nu}_e$ in μ^+ decays at rest was reported by the LSND collaboration in 1995. Subsequent runs at LSND with muons that decay at rest, and in flight, confirmed this initial result to the level of about four sigma. KARMEN running with a different detector configuration, and significantly different neutrino beam geometry, could not confirm the result. A joint analysis [11] was carried out to investigate the probability that the two experiments are compatible. The analysis concluded that the KARMEN result could not completely exclude the LSND signal.

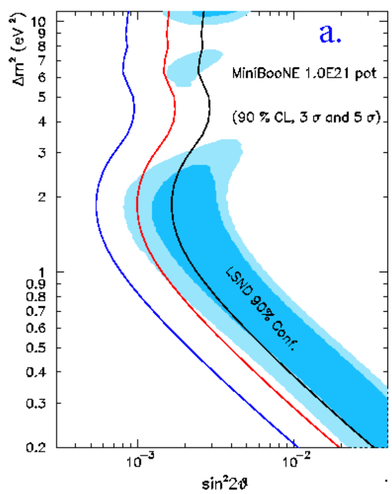
The LSND result, if correct, and combined with the atmospheric and solar results, implies the existence of more than three neutrino flavors. The measured mass differences, one large and two fairly small, cannot be fit into a theory with three neutrino flavors [12]. Collider measurements [13] of the Breit-Wigner distribution of the Z^0 decaying into two leptons preclude the existence of more than three active neutrino flavors. This implies that additional neutrino flavors must be sterile - they would not interact with ordinary matter through the weak interaction.

3.2 MiniBooNE

A detector is now taking data at Fermilab to check the LSND result. MiniBooNE (Fermilab E-898 [14]) is an 800 Ton mineral oil cerenkov counter with 1280 20-cm diameter PMTs positioned at a radius of 5.5 meters relative to the center of the detector. The detector is 12 meters in diameter, and the outer 0.5 meter contains 240 PMTs, which constitute a veto. The detector receives a beam of muon neutrinos generated by the interaction of 8 GeV protons on a 1.7 λ target, and focused by a magnetic horn. After two years of running, the experiment has collected over 380,000 ν_μ interactions.

The search for oscillations in the LSND parameter space is being done as a blind analysis. The collaboration anticipates opening the box in the fall of 2005. The anticipated sensitivity of the search is shown in Figure 1a, with a conservative estimate of systematic errors. The sensitivity of the experiment will depend on the size of the neutrino sample collected, an understanding of the characteristics of the detector, and an understanding of the intrinsic beam-related ν_e backgrounds. The collaboration is actively participating in the BNL E-910 analysis [15], and the CERN HARP experiment [16], to develop a precise model for pion and kaon production on a beryllium target with 8 GeV protons. This should provide an accurate estimate of the ν_μ flux and the intrinsic ν_e backgrounds. In addition, a muon detector is located at an angle of 7° relative to the neutrino beam to collect muons primarily originating in kaon decay [17]. This measurement can be compared to a simulation of neutrinos from kaon decay, which constitute the high energy flux in MiniBooNE. Improvements in analysis are also leading to better background rejection [18]. The collaboration may also use ν_μ interactions in the detector to derive the muon flux in the decay region to estimate ν_e backgrounds from muon decay. By the same process, the pion flux can also be derived so that additional checks can be made on other sources of beam intrinsic ν_e backgrounds. As an additional check for systematic errors, the collaboration has the option of running with a beam stop placed in the middle of the decay region, reducing the neutrino flux from pion decay by 1/2, but leaving the flux from kaon decay nearly unchanged.

Another check for systematics is to run with an entirely different beam configuration. Some data have been taken with the horn focussing system turned off, providing a check of the flux predictions. The collaboration anticipates running with an $\bar{\nu}_\mu$ beam. This configuration may also provide a means to measure CP and CPT violation. We'll get back to this in Section 3.4.



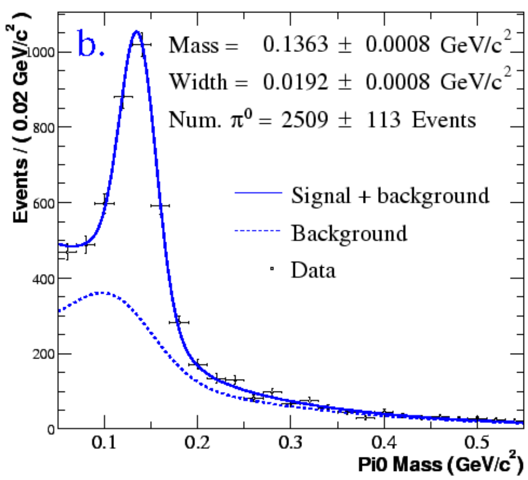


Figure 1: a. MiniBooNE oscillation sensitivity for 1×10^{21} protons on target using fits to the event energy distribution including signal and backgrounds. The dark (light) blue areas are the LSND 90% (99%) CL allowed regions. The three curves give the 90%, 3 σ, and 5 σ sensitivity regions for MiniBooNE. b. Reconstructed invariant mass of π^0s (circles with statistical error bars). Fitted shapes are Monte Carlo calculations of the contribution from background (dashed curve) and signal (neutral current resonant and coherent π^0 production).

3.3 Near-term Measurements

The MiniBooNE collaboration investigates several different phenomena in the process of understanding the detector. The analysis brings up processes for which the experiment can substantially improve existing data. Included are cross-section measurements for charged current quasi-elastic ν_μ scattering, neutral current π^0 production and neutral current elastic scattering.

As an example we may consider the cross-section for neutral current π^0 production. The production mechanism may involve resonant production: $\nu + (p/n) \rightarrow \nu + \Delta$; $\Delta \rightarrow (p/n) + \pi$, or coherent production: $\nu + C \rightarrow \nu + C + \pi^0$. The signal compared to background is given in Figure 1b. With this data it is now possible for the first time to test the models contained in various Monte Carlo simulations [19].

The collaboration is also performing an analysis that will lead to a disappearance search $\nu_\mu \rightarrow \nu \not\mu$ for neutrino oscillations. The analysis will concentrate on a ν_μ quasi-elastic event selection and a good understanding of the energy distribution of the neutrino flux. A disappearance measurement can be used to test specific models that predict the neutrino mass hierarchy, especially those that include sterile neutrinos.

3.4 CP Violation

We mentioned that the MiniBooNE collaboration plans to take data with antineutrinos to help measure systematic effects in the beam and detector. This run may also test for CP-violation by comparing the neutrino and antineutrino oscillation probabilities [20]. This run will take place after the current neutrino run is complete, perhaps in the middle of 2005. The interaction cross-section for $\bar{\nu}_\mu$ is about 1/3 of the ν_μ cross-section, so this may be a very long run. However, the original LSND experiment detected neutrino oscillations in the $\bar{\nu}_\mu$ mode, and it may be that a lack of signal in MiniBooNE could signify the presence of CP violation.

3.5 A Two Detector BooNE

If MiniBooNE sees an oscillation signal, it will be imperative to measure the oscillation parameters with good precision. The addition of a second or third detector will greatly improve the background estimates. The beam intrinsic ν_e will have the same interaction rate per unit volume in each detector, and will cancel out in the analysis. It will be important to have a positive signal in MiniBooNE before the placement of additional detectors, since the most effective location will be an oscillation maximum.

3.6 A Reactor Neutrino Experiment.

The mass mixing matrix (NMS) [21] in the neutrino sector has four free parameters: A parity violating phase δ, and three mixing angles θ_{12} (solar), θ_{23} (atmospheric), and θ_{13} – a special mixing angle that mixes the mass eigenstates related to both solar and atmospheric neutrino oscillations. GUT theories may relate the NMS matrix to the CKM matrix. The mass hierarchy is also not known at this time, and must be inferred from future experiments. These measurements will require great precision and operation of experiments under differing conditions, and with different sources. There are also important differences between oscillations that originate in a $\bar{\nu}_e$ beam compared to a ν_μ beam. In particular, experiments that use a reactor [22] as a source will sit in a beam of $\bar{\nu}_e$. These experiments will be able to measure θ_{13} unambiguously, that is, the oscillations will not depend on θ_{23}. Experiments such as T2K [23] and Nova [24], which sit in a ν_μ beam, will see oscillations that depend on both θ_{13} and θ_{23}. Combining the result of both sets of measurements can yield an unambiguous result for both $\theta_{13}$and θ_{23}. A recent study [25] made a comparison between different detectors, and the physics reach achievable with combined data from each.

3.7 Other Neutrino Experiments.

Two additional measurements I would like to discuss are the measurement of the strange spin of the proton and a measurement of the Weinberg (or weak mixing) angle in $\bar{\nu}_e$ interactions.

The FINeSSE experiment, proposed initially for Fermilab [26] and subsequently submitted at BNL, is designed to perform a precision measurement of the strange spin of the proton (Δs) competitive with the most recent measurements from charged-lepton scattering experiments. By measuring the ratio of neutral-current neutrino-proton elastic scattering to charged-current neutrino-nucleon quasi-elastic scattering to 5%, FINeSSE can measure Δs to an absolute error of $\delta\left(\Delta s\right) = 0.04$.

The measurement of the Weinberg angle would be carried out in conjunction with the reactor θ_{13} experiment. For the θ_{13} measurement the signal is taken from quasi-elastic interactions, making a comparison between near and far detectors. The measurement of $\sin^2(\theta_W)$ relies on a measurement of antineutrino electron elastic scattering. The total rate of this process is sensitive to $\sin^2(\theta_W)$ [27].

4 Conclusion

We've discussed several current issues in this paper. The leptons and quarks have much in common in grand unified theories. Neutrino experiments will play a vital role in establishing good quantum numbers in unified theories. In particular, neutrino experiments will determine if sterile neutrino families should be added to the mass mixing matrix; a comparison of neutrino and anti-neutrino oscillations will provide an excellent laboratory for tests of CP; reactor experiments, combined with accelerator-based experiments, will unravel the neutrino mass mixing matrix; and comparison of oscillation phenomena in $\bar{\nu}_e$and ν_μ beams can lead to tests of CPT. Additional measurements in neutrino beams will determine the strange spin of the proton, and a reactor experiment can measure the Weinberg angle in a unique and interesting channel.

And finally, the fine words of Reginald Butler notwithstanding; nay – one cannot arrive at a destination at a time before departure, even if one invokes the special theory [28].

Acknowledgements

The author wishes to thank the MiniBooNE collaboration for their help in preparation of this presentation.

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